

Power-based Shift Schedule for Pure Electric Vehicle with a Two-speed Automatic Transmission

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Abstract. This paper introduces a comprehensive shift schedule for a two-speed automatic transmission of pure electric vehicle. Considering about driving ability and efficiency performance of electric vehicles, the power-based shift schedule is proposed with three principles. This comprehensive shift schedule regards the vehicle current speed and motor load power as input parameters to satisfy the vehicle driving power demand with lowest energy consumption. A simulation model has been established to verify the dynamic and economic performance of comprehensive shift schedule. Compared with traditional dynamic and economic shift schedules, simulation results indicate that the power-based shift schedule is superior to traditional shift schedules.

1. Introduction

Electric vehicles (EVs) with a multi-speed automatic transmission have become more attractive in recent years on vehicle marketing [1, 2]. Shift schedule is a significant designing factor for EVs equipped with automatic transmission [3]. It will directly affect the drivability and economy of vehicles [4]. Traditional shift schedule is often classified as dynamic shift schedule and economic shift schedule, both considering about only one factor [5]. In order to achieve the driver's power demand with low energy consumption, a comprehensive shift schedule should be widely used in EVs.

There are some optimal methods to optimize the gear selection of shift schedule to improve the vehicle performance [6, 7]. Hou Rui has come up with a dynamic programming (DP) method to optimize shift schedules by changing different control weight. The economic benefit can be increased 0.94-2.28%. However, the dynamic characteristic may be reduced by 1.55-3.52% [8]. Yu Xiang proposed a DP algorithm to map the optimal gear operational points. Simulation result of calculating the battery state of charge (SOC) indicates that the energy consumption economy of EV could be increased 5.5%. But the dynamic characteristic is not mentioned [9]. Lulu Guo presents that both model predictive control (MPC) strategy and DP algorithms could insure the 2-speed EV dynamic performance. MPC could better improve economy performance [10]. In addition, Lulu Guo considers about the road grade and improves the energy efficiency about 6.57% [11].

Some researches just consider about the economic characteristics, but neglect the dynamic performance of EVs. In this paper, the comprehensive shift schedule simultaneously considers the dynamic and economic characteristics. Principles to design the power-based comprehensive shift schedule are proposed. Simulations to compare about three kinds of shift schedule are shown in this paper.

2. The two-speed automatic transmission



The research objective of this paper is a pure electric vehicle with a two-speed automatic transmission. Table 1 is the shift logic and gear ratios. Table 2 shows the design parameters of the EV.

Table 1. The shift logic and gear ratios of the 2-speed automatic transmission.

Gear	Ratio	Shift Clutch	
		C1	C2
1st gear	9.185	engaged	disengaged
2nd gear	5.609	disengaged	engaged

Table 2. The main design parameters of aim vehicle.

Parameter		Value	
Maximum mess m (kg)		2256	
Wind area A (m ²)		2.2	
Coefficient of air resistance C_D		0.35	
Coefficient of rolling resistance f		0.015	
Wheel rolling radius r_w (m)		0.3217	
Maximum speed (km/h)		≥ 150 (instantaneous)	≥ 130 (continuous)
Dynamic	0-100km/h Accelerate time (s)	≤ 13	
	Maximum grad ability (%)	$\geq 30\%$	
Economic	Limited driving distance(km)	NEDC ≥ 100	60km/h ≥ 140
	100km energy consumption(kWh)	NEDC ≤ 18	60km/h ≤ 15

3. Dynamic model of electric vehicle

3.1. Drive motor model

The drive motor output torque T_M is a piecewise function of the accelerator pedal opening α and the motor speed ω_M , separated by base speed ω_{Mb} as:

$$T_M = \begin{cases} \alpha T_{M \max}, & 0 \leq \omega_M \leq \omega_{Mb} \\ \frac{\alpha P_{M \max}}{\omega_M}, & \omega_M > \omega_{Mb} \end{cases}, \quad (1)$$

where α ranges from 0 to 1, $T_{M \max}$ is the maximum motor torque, $P_{M \max}$ is the maximum motor power. Figure 1(a) shows the experimental characteristic curve for the drive motor with different accelerator pedal opening. The following shift schedule in this paper is based on these motor experimental data. Figure 1(b) is the motor efficiency contour and external characteristic curve.

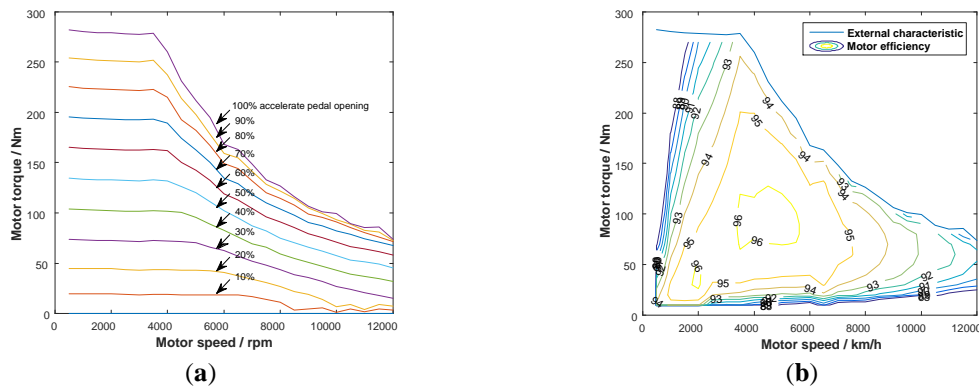


Figure 1. (a) The torque-speed characteristic curve of drive motor; **(b)** The motor efficiency contour and external characteristic curve.

3.2. Automatic transmission model

The function of automatic transmission is selecting a proper gear to change the speed ratio of powertrain. The speed relationship between the input and output of transmission is:

$$\omega_{s2} = \frac{\omega_{s1}}{i_k \cdot i_0}, \quad (2)$$

where ω_{s1} and ω_{s2} are the speed of input and output, i_k and i_0 are the ratio of normally engaged gears and the final reduction gears. When $k=1$, $i_k \cdot i_0$ is the total ratio of the first gear. When $k=2$, $i_k \cdot i_0$ is the total ratio of the second gear.

3.3. Vehicle dynamic model

This model is to calculate the vehicle driving resistance torque. The vehicle speed has a relationship with the transmission output speed ω_{s2} as:

$$v_v = \omega_{s2} \cdot r_w, \quad (3)$$

where v_v is the vehicle speed and r_w is the rolling radius of wheels. The vehicle driving resistance force can be calculated, containing the air F_D , the rolling F_R , and the gradient resistance forces F_G :

$$\begin{aligned} F_D &= \frac{1}{2} C_D A \rho (v_v - v_a)^2 \\ F_R &= fmg \cos \beta \\ F_G &= mg \sin \beta \end{aligned}, \quad (4)$$

where C_D , A , f and m are shown in Table 2. ρ is the density of air, v_a is the speed of wind, g is the gravity coefficient, β is the gradient. Then the vehicle driving resistance torque is:

$$T_{DR} = (F_D + F_R + F_G) \cdot r_w. \quad (5)$$

4. Shift schedule

4.1. Dynamic shift schedule

For a specific vehicle speed v and a specific accelerator pedal opening α , the relationship curve between traction torque and vehicle speed can be obtained with different ratio [12]. The dynamic shift curve can be plotted by connecting intersections for different pedal opening as shown in Figure 2. In order to void cyclic shift, the downshift curve should be delayed 5-10 km/h.

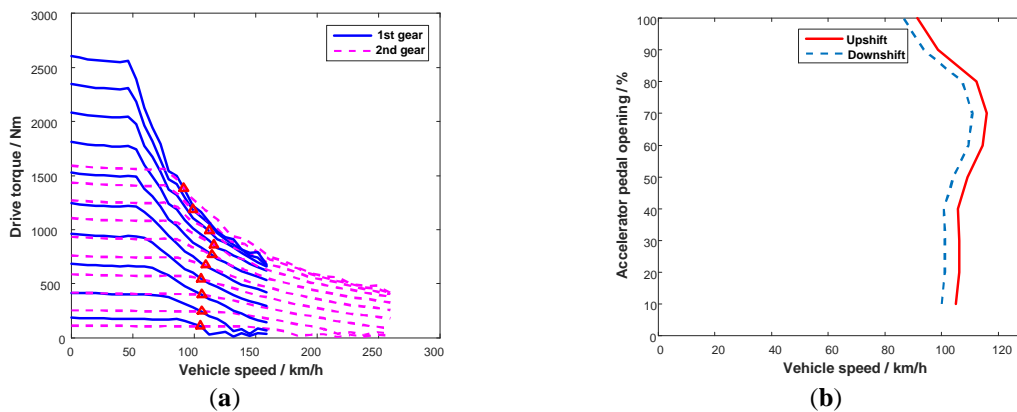


Figure 2. (a) Intersections of drive torque for different pedal opening; (b) Dynamic shift curve.

4.2. Economic shift schedule

Figure 3(a) shows the relationship curve between motor efficiency and vehicle speed in different pedal opening. The economic shift curve is obtained by connecting efficiency intersections [13]. Figure 3(b) shows the economic shift curve. The downshift curve is also delayed 5-10 km/h.

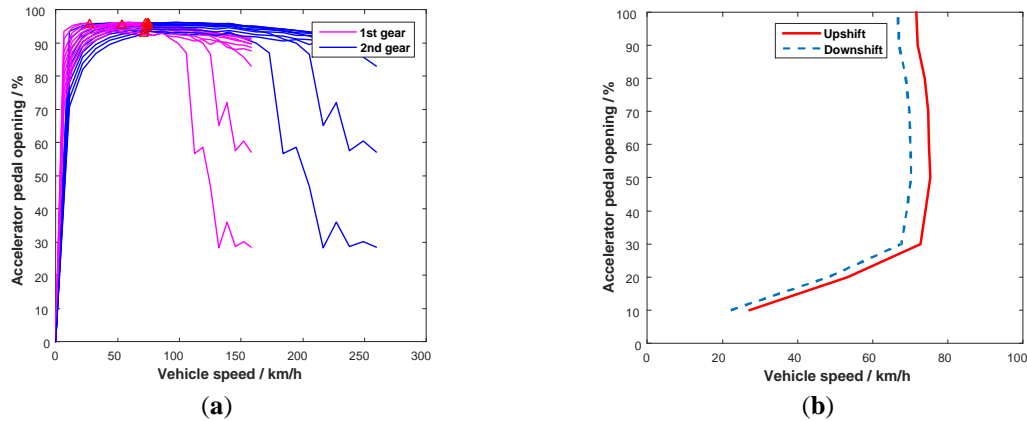


Figure 3. (a) Intersections of motor efficiency for different pedal opening; **(b)** Economic shift curve.

4.3. Power-based shift schedule

The above shift schedules have their limitations due to the only one-factor consideration about the vehicle dynamic or economic performance. This paper introduces a method to draw a power-based shift map to firstly meet the dynamic demand and secondly ensure the motor working in a higher efficiency area. The power-based shift schedule follows these three principles.

4.3.1. Maximum motor speed principle. In this paper, the motor working speed can achieve no more than 7000rpm. The motor speed can be reduced by a certain vehicle speed v and two gear ratios as:

$$n_k = \frac{v \cdot i_k}{0.377 r_w}, \quad (6)$$

where n_k is the k -gear motor speed. Since $i_1 > i_2$, n_1 is larger than n_2 . Thus, the second gear should be the current gear once n_1 exceeds 7000 rpm.

4.3.2. Maximum motor torque principle. For a given vehicle speed v and a given power demand P , the torque request can be counted as:

$$T_{kd} = 9550 \frac{P}{n_k}, \quad (7)$$

where T_{kd} is the k -gear motor torque demand. The motor actual torque $T_k = \min\{T_{kd}, T_{Mmax}\}$. Then the power motor provided is known and the gear with larger power should be selected as current gear:

$$P_k = \frac{T_k \cdot n_k}{9550}. \quad (8)$$

4.3.3. The lowest energy consumption principle. In addition to the above two conditions, for a specific vehicle speed and power demand, the motor efficiency is known according to Figure 1(b). Current gear should be the one with higher efficiency to ensure lower energy consumption.

According to these three principles, the power-based shift map can be drawn as shown in Figure 4.

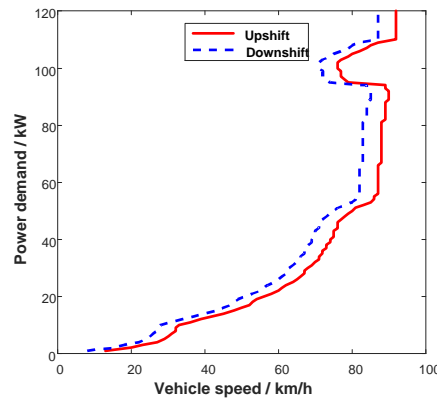


Figure 4. The power-based shift curve.

5. Simulation results and analysis

5.1. Simulation for dynamic performance

Under the 100% accelerator pedal opening, the accelerate time for 0-50 km/h, 50-80 km/h, 0-100 km/h without shift continue time is listed in Table 3. As can be seen, the economic shift schedule accelerates rapidly for 0-50 km/h, while for 50-80 km/h and 0-100 km/h, the drive ability of dynamic schedule and power-based schedule are almost the same, both are superior to economic schedule. The reason of the simulation result is both the dynamic shift and power-based shift schedule firstly consider about the traction performance. While the economic shift schedule ignores the vehicle dynamic ability.

Table 3. Accelerate time for 0-50 km/h, 50-80 km/h and 0-100 km/h.

Shift schedule	0-50 km/h (s)	50-80 km/h (s)	0-100 km/h (s)
Dynamic shift	4.206	3.452	11.088
Economic shift	4.207	3.548	11.214
Power-based shift	4.215	3.450	11.095

5.2. Simulation for economic performance

Comparing to traditional gasoline-powered automotive, the biggest superiority of electric vehicle is the economic performance with low energy consumption. A forward modelling method is adopted in this paper to infer the practical accelerator pedal opening. The energy consumption E_M in accordance with NEDC driving cycles is calculated by integrating the motor output power as:

$$E_{con} = \int \frac{n_M \cdot T_M(n_M, \alpha)}{9550} \cdot \frac{1}{\eta(n_M, \alpha)} dt, \quad (9)$$

where η is the transmission efficiency and other parameters have the same meaning as above.

To satisfy the design demand, 100-km energy consumption is also calculated for uniform velocity 60 km/h. The simulation results are shown in Table 4. Due to the dependence of the accelerator pedal, the power-based shift schedule has a less energy consumption than traditional dynamic and economic shift schedules.

Table 4. 100-km Energy consumption of three kinds of shift schedule.

Shift schedule	NEDC (kWh)	60km/h(kWh)
Dynamic shift	14.46	14.08
Economic shift	14.35	13.59
Power-based shift	14.10	13.59

6. Conclusion

This paper introduces a method to generate the power-based shift curve. It is a comprehensive shift schedule by considering both dynamic and economic characteristics of electric vehicles. Three principles to develop the power-based shift schedule are proposed. As the simulation result illustrates, the comprehensive power-based shift schedule has a fairly driving ability with traditional dynamic shift type. Power-based shift schedule has a strong accelerate ability in 50-80 km/h. Moreover, the energy consumption of comprehensive shift type is the lowest. In NEDC driving cycles, the 100-km energy consumption of power-based shift schedule is less than the traditional economic shift schedule by 2%. The power-based shift schedule regards the vehicle tractive ability and economy performance as the input parameters of shifting schedule. Thus, the motor load power and working efficiency can be improved simultaneously. Therefore, the comprehensive power-based shift schedule should be widely employed in electric vehicles.

References

- [1] Yu, Zhe, S. Li, and L. Tong. "Market dynamics and indirect network effects in electric vehicle diffusion." *Transportation Research Part D Transport & Environment* 47(2016):336-356.
- [2] D., A., Crolla, and Morris. "Effect of Transmission Design on Electric Vehicle (EV) Performance." *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE* 2009:46-51.
- [3] Roberts, Simon. "Multispeed transmission for electric vehicles." *Atz Worldwide* 114.4(2012):8-11.
- [4] Torrelli, Dr. Ing. Claudio. "Transmissions for Electric Vehicles." *Atz Worldwide* 115.2(2013):10-13.
- [5] Qin, Da Tong, et al. "Parameters design of powertrain system of electric vehicle with two-speed gearbox." *Journal of Chongqing University* 34.1(2011):1-6.
- [6] Hofman, T., S. Ebbesen, and L. Guzzella. "Topology Optimization for Hybrid Electric Vehicles With Automated Transmissions." *IEEE Transactions on Vehicular Technology* 61.6(2012):2442-2451.
- [7] Ngo, V., et al. "Optimal control of the gearshift command for hybrid electric vehicles." *IEEE Transactions on Vehicular Technology* 61.6(2012):3531-3543.
- [8] Hou, Rui, J. Zhang, and C. Lin. "New Approach of Comprehensive Shift Schedule Based on Electric Drive Automated Mechanical Transmission ☆." *Energy Procedia* 88(2016):945-949.
- [9] Xiang, Yu, et al. "A Study on Gear Shifting Schedule for 2-Speed Electric Vehicle Using Dynamic Programming." *Chinese Control and Decision Conference IEEE*, 2013:3805-3809.
- [10] Guo, Lulu, et al. "Shift schedule optimization of 2-speed electric vehicle using model predictive control." *Control Conference IEEE*, 2014:156-161.
- [11] Guo, Lulu, B. Gao, and H. Chen. "On-line Shift Schedule Optimization of 2-Speed Electric Vehicle Using Moving Horizon Strategy.".
- [12] Zhu, Bo, et al. "Gear shift schedule design for multi-speed pure electric vehicles." *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering* 229.1(2014):70-82.
- [13] Li, Wei, X. Yin, and X. Wu. "Shift Schedule of Electrical Vehicle based on the Optimization of Motor Efficiency." *Journal of Mechanical Transmission* (2014).